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Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Yi, Y., & Sørensen, J. D. (2019). *Reduction of Operation and Maintenance Cost for Wind Turbine Blades – Reliability Model*. Department of Civil Engineering, Aalborg University. DCE Technical Reports No. 260

DEPARTMENT OF CIVIL ENGINEERING
AALBORG UNIVERSITY

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ISSN 1901-726X
DCE Technical Report No. 260

Aalborg University
Department of Civil Engineering
Group Name

DCE Technical Report No. 260

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by

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January 2019

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Published 2019 by
Aalborg University
Department of Civil Engineering
Thomas Manns Vej 23
DK-9220 Aalborg Ø, Denmark

Printed in Aalborg at Aalborg University

ISSN 1901-726X
DCE Technical Report No. 260

Contents

1. Introduction

1.1 Background

The primary purpose of this report is to document the theoretical methodologies used to construct the reliability model which is the main work scope of Deliverable D1.1 in Work Package 1 (WP1). The reliability model is closely associated with WPs 4, 5 & 7 which focus on the investigation into failure mechanisms by means of the fracture mechanics study and the laboratory tests (at a coupon level, a sub-component level or at a full-scale level). It is important to develop and describe the probabilistic model as basis for reliability analyses and to obtain probabilistic models for the rate of crack/defect propagation for a specific failure mechanism.

Generally speaking, damages which wind turbine (WT) blades are subjected to can be classified from two perspectives of failure mechanisms, i.e. mechanical damages and non-mechanical damages. Mechanical damages are basically caused by both ultimate and cyclic loadings. Overstress and buckling are the common failures caused by the ultimate strength loadings (causing progressive degradation or sudden failure), while fatigue cracks/ defects are caused by cyclic loadings. Non-mechanical damages stand for the deterioration of materials due to non-mechanical actions or indirect mechanical actions, such as erosion, flaking, lightening, etc. Due to the considerable increase in cleaner energy demand, there is a significant trend of increased WT sizes, which results in much higher loads on the blades. The high loads can cause significant out-of-plane deformations of the blade, which may result in especially 'Transverse cracks' and 'Root area& Transition zone cracks'. Fatigue-induced mechanical damages, especially the aforementioned two critical areas, are the primary concern to be addressed in the RATZ project. After the failure mode is identified, the next two questions are: which model(s) can be developed to predict the crack/defect propagation in a relatively conservative manner, and which can be used for reliability assessments. Generally, the crack/defect propagation is subject to many uncertain internal and external agents/influences, which make the crack/defect propagate randomly. Therefore, a probabilistic crack/defect propagation model will be developed which constitutes the basis of the reliability model. The predictability of a reliability model is highly dependent upon the availability of high quality input data. According to the quality of input data, two levels of modelling procedures will be presented in Section 2.4. The simulation-based method is focused in the RATZ project.

Based upon the reliability model, the stochastic process of crack/defect propagation can be defined as either a continuous or a discrete function of time. A decision maker does not care too much about how accurately the probabilistic crack/defect propagation model can predict the crack/defect size. What the decision maker could be interested in are questions such as:

- Globally speaking, how long time it takes for an initial defect to propagate to a critical size, namely the lifetime before a corrective maintenance has to be done;
- If the decision maker knows how severely the blade is currently damaged, how much longer is the damage to stay at the current damage state before it jumps to a more severe state, and when non-destructive testing inspections should be conducted and the necessary preventive maintenance should be planned.

Based upon these considerations, a five-level damage categorization scheme is applied and is based on a similar scheme used by WT designers, operators and owners. In such a damage categorization scheme, a continuous crack/defect propagation process is discretized into a few categories, each of which covers a range of crack/defect sizes, which will be detailed in Section 2. The theoretical basis, as well as the procedures for developing such a reliability model, will be documented and described in the subsequent sections of this report.

With a well-defined reliability model, realizations of stochastic crack/defect propagation time series can be generated, which is a basic input for decision-making. The decision-making process, as well as the estimation of maintenance expenses, constitutes the basis of a cost model. The actions that a decision maker takes depend upon the maintenance strategies that will be detailed in another separate report (Cost modelling and decision-making ISSN 1901-726X DCE Technical Report No. 261). An optimal maintenance strategy plays an important role in securing the structural integrity of WT blade structures and minimizing the operation and maintenance (O&M) costs. On the contrary, a poor maintenance strategy causes an economic loss. For instance, if one crack/defect is undetected or detected but no action is conducted in time, the crack/defect could propagate in an uncontrollable manner and result in a total blade collapse which causes a severely economic loss to WT owners. Therefore, the main question is what can be done to prevent the total collapse or major repair of WT blades, while keeping the maintenance/repair costs within a reasonable range that a pre-allocated budget allows. It is a trade-off between the tolerable risk undertaken for a blade and the O&M costs to ensure its structural integrity – this will be addressed in RATZ project for two aforementioned critical areas ('Transverse cracks' and 'Root area& transition zone cracks'). The reliability model developed in this report will provide a way to statistically simulate the damage propagation which is the input to the decision-making process. Of all the possible maintenance strategies, the cost-optimal one will be finally chosen.

1.2 Literature Review

The research regarding the reliability modelling for O&M planning of WT blades has been a hot topic over the past two decades. A thorough understanding of damage propagation is a prerequisite of constructing an informative probabilistic model for the subsequent O&M planning. The essential part of a reliability model is the simulation of crack/defect propagation. The methodology regarding crack/defect propagation can be generally divided into three categories. Category 1 is a physics-based model in which a general degradation path (also known as failure path) is calibrated based upon both the fracture mechanics theory and the laboratory tests. Category 2 is a type of data-driven method, which is only based upon the information extracted from a database. Category 3 is a hybrid of the physics-based and the data-driven methods. On the one hand, a stochastic process is defined to qualitatively characterize the damage evolution. On the other hand, a large amount of in-history observations/records should be used to calibrate the model parameters. Literature review focuses on the research findings of Category 1& 3 in this report.

Some typical research findings regarding Category 1 are summarized in this paragraph. Generally, there are plenty of factors influencing the crack/defect onset and propagation in composite materials. A physics-based model (fracture mechanics model) is only a tailor-made model developed for a specific failure mode at a specific position along the blade profile (e.g. cracks on transition zone, transverse cracks at the maximum chord, cracks on the training edge, etc.). Theoretical studies, as well as laboratory tests, haave been performed for different failure modes. A few typical fracture mechanics models will be only presented in this section. Shipsha et al. prepared two types of specimen, namely, Double Cantilever Beam (DCB) and Cracked Sandwich Beam (CSB), to perform constant-amplitude fatigue tests [1]. The aim of the tests is to verify the predictability of two assumed failure paths, namely, Mode I for DCB and Mode II for CSB for the interfacial crack behaviour. They found a trend of crack propagation that is similar to that for metallic materials (i.e. stage 1: initiation; stage 2: stable crack propagation; stage 3: unstable crack propagation), and calibrated the test data for stage 2 to the well-known Paris-Erdogan law. Ronald et al. presents a benchmark example for cyclic delamination propagation prediction [2]. The benchmark example is based upon a finite element model of a DCB for Mode I. The number of cycles to delamination onset and the number of cycles during stable delamination growth for each growth increment are obtained from the analysis. Liu and Mahadevan proposed a simple and versatile damage accumulation model for multiaxial fatigue problem in laminated composites, and predicted the fatigue life of composite laminates based upon this model [3]. From the perspective of fatigue-induced failures, Dimitrov proposed a design methodology for WT blades where a stochastic fatigue analysis model based upon S-N curve was developed [4]. The uncertainties of both loads and intrinsic material properties were considered in his thesis. Dimitrov et al. investigated the spatial reliability of WT blades by taking into account loading directions, spatial correlation between random material properties, progressive material failure and system reliability effects [5]. Sørensen et al. developed a general fracture mechanics test configuration for characterizing mixed mode crack growth and investigated the crack propagation in adhesive joints between composites made of thermoset glass fibre reinforced plastic [6]. Saseendran and Berggreen proposed a novel test-rig exploiting the double cantilever beam-uneven bending moments (DCB-UBM) concept is used to determine the fracture toughness of aircraft type honeycomb core sandwich composites as a function of the phase angle (mode-mixity), within the framework of Linear Elastic Fracture Mechanics (LEFM) [7]. Larsen et al. proposed a modified test procedure that allows direct measurement of mixed-mode cohesive laws for interfaces in sandwich structures, by bonding stiff layers onto the sandwich faces to increase the bending stiffness [8].

A few representative research findings regarding Category 2 are summarized in this paragraph. Nielsen and Sørensen proposed a discrete Bayesian Network for risk-based planning of inspection, maintenance and condition monitoring of wind turbine components [9].

Some typical research findings regarding Category 3 are summarized in this paragraph. Sørensen presented a general framework for rational and optimal O&M planning, based upon a risk-based life cycle decision-making model [10]. Florian and Sørensen adopted the fundamental idea behind the model developed by Sørensen and presented the application of this model to a general cost-optimal planning for WT components [11- 13]. Chan and Mo developed a Maintenance Aware Design Environment model, which is based upon failure mode and effect analysis and bond graph modelling, to simulate the effects of maintenance strategies on the life-cycle costs of mechanical components of WTs [14]. Carlos et. al. used Monte Carlo simulation to generate random failure times to calculate the cost of corrective maintenance and the unavailability due to downtime, with the aim at maximizing the annual energy generation and minimizing the maintenance cost [15]. Toft and Sørensen discretized the damage evolution into some discrete damage categories, and used the least square algorithm to estimate the transition probabilities based upon the observations of those damage categories extracted from a failure database [16]. The model developed by Toft and Sørensen is a discrete Markov Chain Model which probabilistically depicts how fast a crack/defect propagates from one damage state to a more severe state. Typical methodologies of damage propagation simulation have been reviewed for the application of WT components. The other typical industrial applications of Category 3 will be reviewed in the next paragraph.

Yuan proposed a Gamma-process-based model to simulate the deterioration process of industrial devices, especially stochastic process of corrosion of power plant components and modeled the PM actions [17, 18]. Pandey et al. introduced a Gamma process to model an uncertain general degradation process which was used to simulate the probability distribution of repair/maintenance intervals, and estimated the expected maintenance cost, as well as the standard deviation of cost [19, 20]. The model proposed by Pandey et al. only considered a general type of damage and accordingly estimated the cost and downtime. The Gamma process model parameters were just extracted from a database.

The reliability model can be constructed based upon each of these three methodologies. According the available data at hand, it is determined to use the method(s) of Category 3 to construct the reliability model. In principle, the reliability model developed in this report should be applicable to the two aforementioned critical areas ('Transverse cracks' and 'Root Area& Transition Zone Cracks').

1.3 Objectives

The general objective of reliability modelling is to formulate a probabilistic model which describes the damage evolution with time, based upon the information from Guide2Defect (G2D) and a probabilistic damage propagation model. The model parameters should be calibrated against the laboratory test data and/ or G2D database. A detailed descriptions of the objectives are listed as follows:

- To propose a five-level damage categorization scheme for two critical areas 'Transverse cracks' and 'Root Area& Transition Zone Cracks') based upon the discussions during an internal expert review meeting;
- To propose a reliability model based upon fracture-mechanics-based failure analysis model;
- To propose a reliability model based upon a Discrete Markov Chain Model with the model parameters calibrated against the information extracted from Guide2Defect database;
- To perform a case study by using a reference project depicted in a report issued by National Renewable Energy Laboratory (NREL) and briefly present the interface between reliability modelling and cost modelling (namely how the output in a reliability model can be integrated into a decision-making process).

1.4 Report Outline

The outline of this paper is as follows:

- Section 2 presents the methodology for reliability modelling;
- Section 3 presents a case study, including both base case and sensitivity study;
- Section 4 contains conclusions and recommendations.

1.5 Acronyms

CBM	Condition-based Maintenance
CM	Corrective Maintenance
CVI	Close Visual Inspection
*D*i	Damage Category *i*
G2D	Guide2Defect
GVI	visual inspection
MTTF	Mean Time to Failure
NDT	Non-destructive Testing
NREL	National Renewable Energy Laboratry
O&M	Operation and Maintenance
PoD	Probability of Detection
RATZ	Root Area & Transition Zone
VI	Visual Inspection
WP	Work Package
WT	Wind Turbine

2. Methodology

2.1 Damage Categorization

Damage categorization can be used as a basis for decision making. Generally, which damage severity a specific crack is classified as is closely related to the consequence that this crack results in. The damage categorization in the RATZ project is based upon the general G2D approach, as illustrated in Figure 1. The basic idea of five-level damage categorization scheme will be adopted as a general guidance for categorizing damages in this report.

In the real engineering practices, the number of damage severity levels, as well as crack thresholds, can be adjusted accordingly to be applicable to a specific failure case, e.g. 'Transverse cracks' or 'Root Area& Transition Zone Cracks'. The damage severity level can be determined out of the following considerations:

- The same crack on the same position of different blades from different design (e.g. different composite materials and different geometries of blades) may result in different consequences;
- The fact that different cracks with the same size but observed in different positions may result in different consequences.

The aforementioned two aspects can be addressed by engineering experience (also known as expert system) and structural integrity assessment. On the one hand, engineering experience is based upon the observations of failure events observed in history, and the categorization of damages is done based upon the consequences which the damages can result in. The basic knowledge obtained during categorization is generally specific to individual existing design specifications or some specific failure modes. On the other hand, a structural integrity assessment, like the simplified crack/defect propagation model presented in Section 2.4.2 or Discrete Markov Chain Model presented in Section 2.4.3, is a semi-analytical method to quantify the failure frequency of a specific failure mode and estimate the corresponding consequence when that failure mode occurs. Engineering experience can provide some guidance for reliability modelling of a specific failure mode, based upon in-history failure observations.

An internal expert review meeting has been held to integrate the engineering experience obtained by work package partners. For 'Transverse cracks', the five-level damage categorization scheme, as illustrated in Figure 1, are used and the crack thresholds shown in Table 1 are assumed to be used in the RATZ project. Theoretically speaking, the same damage categorization scheme can be applied to the Root Area& Transition Zone Cracks', with the damage thresholds slightly modified. In reality, the in-history records of the damage propagation of 'Root Area& Transition Zone Cracks' is seldom publically released by the WT owners. The five-level damage categorization scheme is still used to 'Root Area& Transition Zone Cracks'. The transition probabilities for 'Root Area& Transition Zone Cracks' are taken as dummy values based upon engineering experience instead of being calibrated against observations.

Figure 1 Illustration of Damage Categorization

Table 1 Approximate Thresholds of Damage Sizes for Different Damage Categories – 'Transverse Cracks'

Category No.	Damage Description	Damage Sizes [m]
0	Almost Intact	0
1	Cosmetic Damage	0~0.05
2	Minor Damage	0.05~0.20
3	Medium Damage	0.20~0.50
4	Serious Damage	0.50~1.00
5	Critical Damage	1.00 ~ 0.4 times the blade max. chord length

2.2 Fundamental Assumptions for Reliability Modelling

Reliability assessment on WT blades is influenced by two major sources of uncertainties. The first source of uncertainty stems from 'external' influences/agents, e.g. stochastic loadings and boundary conditions. The second source of uncertainty is related to internal/intrinsic material-related properties, e.g. stochastic behaviour of material parameters, initial defects caused by a manufacturing process, anisotropic material resistance to external loads, and crack propagation paths. Some fundamental/general assumptions regarding the two types of uncertainties are made in this sub-section and will be used as a basis for the reliability model.

Stochastic loads

Stochastic modelling of loads is generally not included in the RATZ project. Generic stochastic models for loads based on background documents for IEC 61400-1 ed. 4 are used [21]. However, some typical loads and load effects are considered in WPs 4 & 5. It is implicitly assumed that the blades (and the defects considered) are subject to loads representing typical fatigue loads for the specific wind turbine class for which the blades are designed.

Intrinsic composite material properties

This type of uncertainty includes the uncertainties of the intrinsic material properties, the uncertainties of initial defects etc., which are detailed as follows.

- A wind turbine blade is made of laminates, each of which is constructed by stacking a number of laminae in the direction of the lamina thickness. A lamina is a thin layer of composite materials which consist of glass/ carbon fibers bonded by matrix materials. The composite material properties of a wind turbine blade are inhomogeneous in a full-scale sense due to the uncertainties associated with a specific manufacturing process. The mechanical parameters characterizing the composite material properties, typically including tensile/ compressive strength, Elastic modulus, Poisson's ratio, should generally be modelled by stochastic variables.
- Initial cracks / defects
  - The quality of manufactured composite materials is influenced by some external influences/agents, such as the environmental conditions (temperature and humidity), the technician qualifications, and the manufacturing specifications (e.g. curing). Due to these external influences/agents, some imperfections are initially introduced, such as voids, incomplete curing of the resin, improper fibre/matrix bonding. Due to the inhomogeneity, cracks/ defects will stem from the weakest point/ element which is randomly scattered in a wind turbine blade;
  - Ideally it is assumed that only one (critical) initial defect is present for one wind turbine blade.;
  - The initial defect / crack size is modelled by a probability distribution of initial defect size which might be estimated based upon information on the manufacturing process(es) or the experience of laboratory technicians, e.g.
    - the same order of magnitude as pre-machined cracks used in laboratory tests;
    - the tolerant damage size from a damage-tolerant design – which should be a reasonable indicator of the initial defect size.
- Crack development / growth

- Mode-I (opening mode) is assumed;
- Basic assumptions for LEFM apply:
  - The tip of a defect/ crack is sharp;
  - Linear and elastic load-deflection behavior of a wind turbine blade;
  - The 'crack-tip plastic zone' is relatively small.
- A two-step crack propagation model can be used. In the following only 'Transverse cracks' are considered. For Step-1, an initial crack is located somewhere in the cross-section of one blade. It starts propagating under the external loadings, no matter how fast it propagates. It is assumed that the stay duration (T_1) of Step-1 is a stochastic variable and the crack propagation is stable (i.e. crack propagation rate is almost a constant). When the crack propagates to a critical size, it starts propagating along the through-thickness direction, reaches to the outer fibre of the blade surface, and propagates on the surface. This process is called Step-2. The stay duration (T_2) of this step is a stochastic variable as well. Crack propagation on the surface is 'grouped' into those damage categories as presented in Section 2.1. The assumption is schematically illustrated in Figure 2. *D*i (i=1, 2, 3, 4, 5) denotes the damage category *i* according to the five-level damage categorization as illustrated in Figure 1. Besides these five damage severity levels, two more damage states are added, namely an intact state (D0) and a collapse state (D6, the absorb state in the Discrete Markov Chain Model), which will be detailed in Section 2.4.3.

▪ Composite material toughness
- Stress intensity factor used to approximately characterize the composite material toughness;
  - Unlike the metallic materials, the stress intensity factor may not be a function of crack size. So, ΔK is assumed to be an independent stochastic variable.

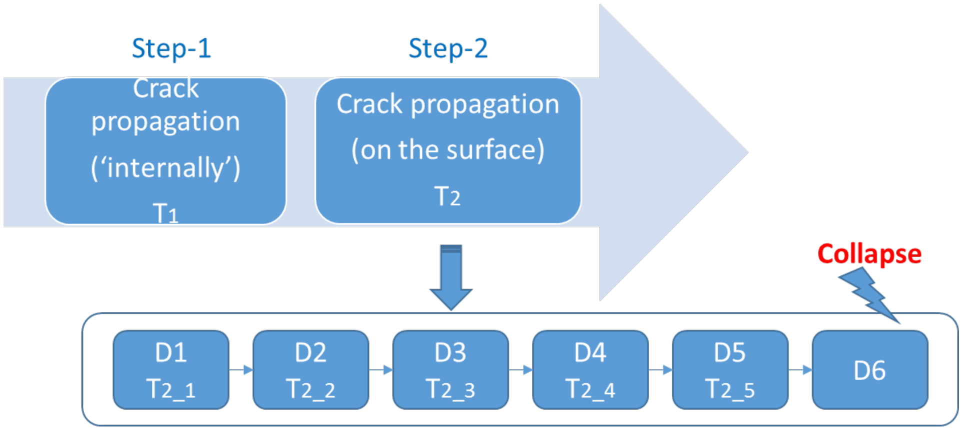


Figure 2 Probabilistic Illustration of Crack Propagation

2.3 Probability of Detection

2.3.1 Overview

Due to the intrinsic uncertainty associated with any non-destructive testing (NDT) procedure, information is needed about the probability of detection (PoD) of a damage with a given size. The PoD is used to quantify the ability of an NDT procedure for detecting a damage with a given size. For WT blades, there are a few NDT procedures that are usually used.

▪ Visual inspection, including the following specific applications
  - Rope access
  - Drone with a camera
  - A man standing on the ground or, the floor or the ship with a camera

▪ Ultrasonic testing
▪ Acoustic emission
▪ Thermography
▪ Shearography

The concept of PoD was first introduced for welded joints of steel structures. Based upon the experience obtained in steel structures, the PoD is usually obtained by physical tests with a number of technicians and is expressed as a function of flaw size (i.e. length or depth), although in reality it is a function of many other physical and operational parameters, such as, the material, the geometry, the flaw type, the NDT method, the testing conditions and the NDT personnel (e.g. their certification, education and experience). The in-depth discussion of PoD is out of work scope of this WP. So, the PoD for composite materials of WT blades is assumed to be derived in a similar manner.

It is noted that the PoD is defined as the probability that a defect / crack of a given size and location is detected by a given inspection technique with a 'typical' person performing the inspection. For example, a large surface crack has typically a large probability of being detected by visual inspection, whereas an internal crack has a very low probability of being detected by visual inspection but a larger probability by e.g. thermography.

2.3.2 NDT Formulation

In this sub-section, the PoD model for visual inspection (VI) is only described, because visual inspection is the most common inspection method applied to detect the defects in WT blades. It is noted that the other non-destructive testing methods are underdevelopment and are expected to be useful in the future for blade inspections.

2.3.2.1 Visual Inspection (VI)

VI includes both general visual inspection (GVI) and close visual inspection (CVI). Similar to the other energy industries (oil & gas, nuclear power plants, etc.), GVI and CVI have traditionally been recommended for WT blades, with the purpose of control for gross damages/ defects. GVI and CVI may also have a positive effect on reliability with respect to fatigue. As the name indicates, close visual inspection requires a technician or a device to approach closely to the target object as possible.

Nowadays, VI is the most common NDT method used in the on-line inspection of WT blades. However, there is little information on PoD of VI. Expert review meetings chould be used for estimating probabilities of detection for the five damage categories in the damage categorization scheme. Generally, the PoD is related to the external environmental influences and the technicians' qualification. During the expert review meetings, the scenarios where the combination of these factors influencing the PoD should be documented and discussed. With the aim to achieve this target, a template of is proposed for the experts to quantify those discrete probabilities, as summarized in Table 2, in which one combination of environmental condition and the technician qualification is summarized. For the time being, there are only two criteria (Qualification/ Condition) listed in this table. The detailed investigation into the human and device reliability is out of the work scope of the RATZ project. Some general criteria are proposed to judge the probability of detecting a damage. Probably more criteria can be integrated into this questionnaire, based upon more potential project participants in wind industry. It is noted that additional physical tests could be performed where a number of inspectors inspect the same blade(s) with known crack size(s).

Table 2 Proposed Template for Quantifying Discrete PoD of VI

VI Methods	Qualification/Condition	Weather Limit	Detectability	Damage Category	Probability of Detection
Rope access	A highly qualified/experienced technician conducting the VI	Gentle wind, high visibility, moderate temperature	High	DC1	P_{DC1}
				DC2	P_{DC2}
				DC3	P_{DC3}
				DC4	P_{DC4}
				DC5	P_{DC5}
		Stronger wind, marginal visibility, lower temperature	Medium	DC1	P_{DC1}
				DC2	P_{DC2}
				DC3	P_{DC3}
				DC4	P_{DC4}
				DC5	P_{DC5}

Notes:
1. Scale of Probability: 'High' – >80%; 'Medium' – 50%~80%; 'Marginal' – 20%~50%; 'Poor' – <20%;
2. A technician's qualification is mainly based upon his/her previous work performance and the professional certificates;
3. A device condition mainly depends upon the routine maintenance records and the validity of the equipment certificate(s).

2.4 Reliability Model

2.4.1 Overview

The accuracy of a reliability model is highly dependent upon the availability of good data. According to the quality of input data, two options of modelling procedures are briefly summarized below and will be presented in the following sub-sections.

- Option 1: Simplified probabilistic crack propagation Model based upon fracture mechanics failure analysis;
- Option 2: Discrete Markov Chain Model based upon the information from Guide2Defect failure database, which is the primary option in the RATZ project.

2.4.2 Simplified Probabilistic Crack Propagation Model

2.4.2.1 Formulation

The crack propagation of composite materials is more complicated than for steel structures. Based upon the assumptions made in Section 1, a simplified probabilistic crack propagation model may be developed for the consecutive reliability assessment and O&M cost estimation. The requirements on such a simplified model are as follows:

- The model should be a closed-form analytical or semi-analytical crack propagation model which can be established based upon a more complex fracture propagation modelling and can be verified by finite element analysis;
- The model should be sufficiently simple and able to be implemented and operated as a part of a probabilistic reliability modelling scheme in O&M planning.

A simplified crack/ defect propagation model is assumed to take the same form of that for welded steel structures, which is given by Eq. (1).

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

where C and m are material parameters. ΔK is the stress intensity factor range, which is a function of crack size and fatigue load.

2.4.2.2 Relation between Damage Categorization Scheme and Probabilistic Crack Propagation Model

The continuous crack propagation as defined in Eq. (1) is discretized to a few groups, each of which corresponds to one of the damage severity levels presented in Section 2.1. The discretization may be illustrated as shown in Figure 3.

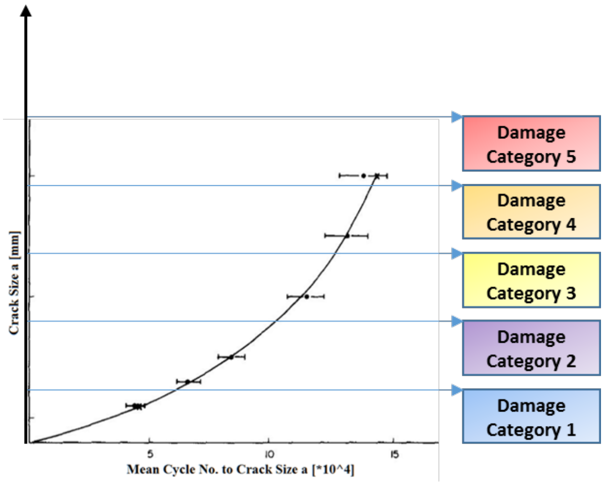


Figure 3 The Relation between Crack Size a and Mean Cycle No. ($\mathrm{E}[\mathrm{N}(\mathrm{a})]$)

2.4.3 Discrete Markov Chain Model

2.4.3.1 General Formulation

As a hybrid of the physics-based and the data-driven methods, the Discrete Markov Chain Model does not require a closed-form equation characterizing the physical crack/defect propagation, which extends the application of the Discrete Markov Chain Model. The physical damage propagation mechanism is implicitly included in the Discrete Markov Chain Model in a simplified way. In-history inspection records of blades with different design specifications are extracted from an inspection database and used to calibrate the transition probabilities in the Discrete Markov Chain Model, see below. The records are classified into groups based upon a six-level damage categorization scheme, namely damage category 1 (D1, the most minor state) to damage category 6 (D6, the total collapse state)

With consideration of the physical process of crack/defect propagation, the Discrete Markov Chain Model is assumed to be a unit-jump model. For this case, there are only two possibilities at each state, i.e. remaining in the current state with the probability of p_i (i=1, 2,...,b, where b is the failure state (i.e. the total collapse of a blade)/ absorb state) or transferring to the next state with the probability of q_i (for each i, p_i+q_i=1) , as illustrated in Figure 4. The initial probabilities of each state being $P_0 = \{1, 0, \dots, 0, 0\}$. The transition probability matrix is given in Eq. (6).

$$\boldsymbol{P_T} = \begin{bmatrix} p_1 & 0 & 0 & \dots & 0 \\ q_1 & p_2 & 0 & \dots & 0 \\ 0 & q_2 & p_3 & 0 & 0 \\ 0 & 0 & q_3 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

After x transitions, the probabilistic distribution of each state is expressed by:

$$P_s = P_0 P_T^x \tag{3}$$

The transition probabilities are initially calibrated to minimize the object function defined in Eq. (8) based upon Least Square approximation method.

$$F_{obj} = min\left[\sum_{i=1}^{b}\left(N_{obs,i} - N_{est,i}\right)^2\right] \tag{4}$$

$$N_{est,i} = P_i * N_T \tag{5}$$

where *i* denotes the different damage states. $N_{obs,i}$ is the number of observations for damage category *i* and $N_{est,i}$ is the estimated number of damages for damage category *i*, by using the Discrete Markov Chain Model with calibrated transition probabilities. N_T denotes the total number of observations extracted from Guide2Defect database. Additionally, information from inspections of the same crack / defect at subsequent inspections should be used in the calibration.

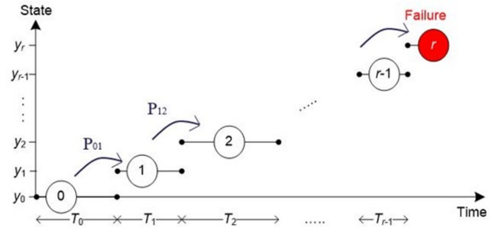


Figure 4 Schematic Illustration of Discrete Markov Chain Model

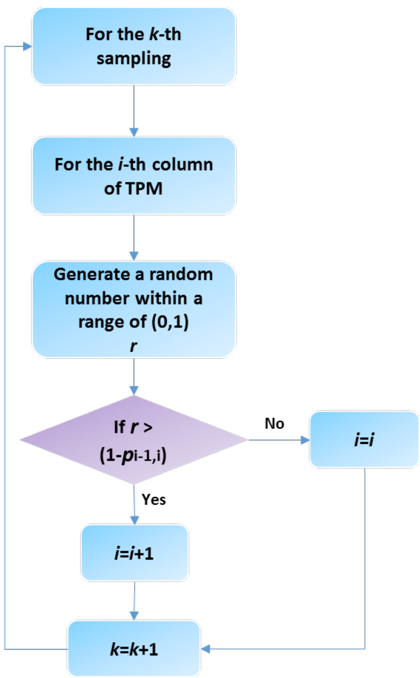
2.4.3.2 Sampling Algorithm based upon Markov Chain Model

With the aim to keep consistent with the five-level damage categorization scheme in G2D, there are five damage states defined in Discrete Markov Chain Model. The damage severity levels can be abbreviated as *D*i (i=1, 2, 3, 4, 5) according to the five-level damage categorization as illustrated in Figure 1. Besides the five damage states (damage severity levels), there are two more states needed in the Discrete Markov Chain model, namely an intact state (D0) and a collapse state (D6, the absorb state in the Discrete Markov Chain Model). The purpose of defining these two states is to satisfy the theoretical criteria in the Discrete Markov Chain Model, namely there must be an intact state from which a Markov Chain starts jumping, and an absorption state which represents the end of a Markov process.

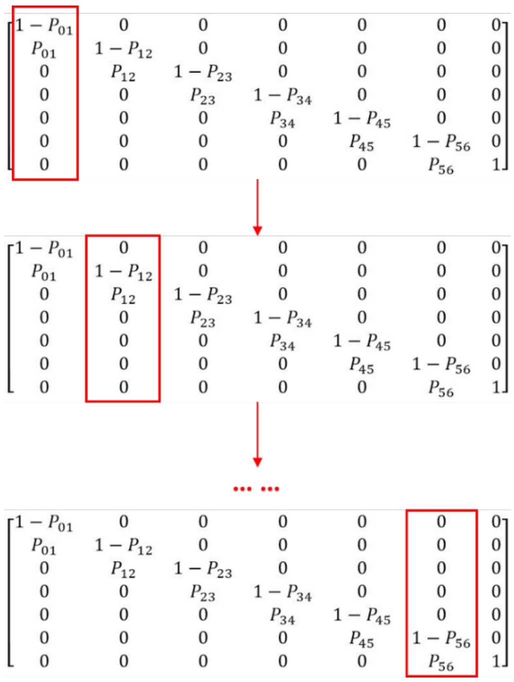
In Discrete Markov Chain Model, the jump from one damage state to the next more critical state is simulated by random sampling as illustrated in Figure 6 (a). For instance, the damage evolution starts with the intact state (D0). Sample a number within the interval of (0,1) and compare it with the cumulative sum of the 1st column entries of the transition probability matrix from the 1st entry to the one on the main diagonal, i.e. (1- P_{01}). If the number is greater than (1- P_{01}), that indicates the damage has propagated to 1st damage state. To simulate the jump from the 1st damage state to the 2nd damage state, the procedures are almost the same, but the cumulative sum is taken for the 2nd column entries of the transition probability matrix. Repeat the aforementioned procedures for the other jumps until the last damage state, namely the absorb state in the Discrete Markov Chain Model. The general transition probability matrix in Eq. (10) is changed to a concrete form as given in Eq. (6).

$$\boldsymbol{P_T} = \begin{bmatrix} 1-P_{01} & 0 & 0 & 0 & 0 & 0 & 0 \\ P_{01} & 1-P_{12} & 0 & 0 & 0 & 0 & 0 \\ 0 & P_{12} & 1-P_{23} & 0 & 0 & 0 & 0 \\ 0 & 0 & P_{23} & 1-P_{34} & 0 & 0 & 0 \\ 0 & 0 & 0 & P_{34} & 1-P_{45} & 0 & 0 \\ 0 & 0 & 0 & 0 & P_{45} & 1-P_{56} & 0 \\ 0 & 0 & 0 & 0 & 0 & P_{56} & 1 \end{bmatrix} \tag{6}$$

In Discrete Markov Chain Model, the jump from one damage state to the next more critical state is simulated by random sampling as illustrated in Figure 5 (b). For instance, the damage evolution starts with the intact state. Sample a number within the interval of (0,1) and compare it with the cumulative sum of the 1st column entries of the transition probability matrix from the 1st entry to the one on the main diagonal, i.e. (1-P_{01}). If the number is greater than (1- P_{01}), that indicates the damage has propagated to 1st damage state. To simulate the jump from the 1st damage state to the 2nd damage state, the procedures are almost the same, but the cumulative sum is taken for the 2nd column entries of the transition probability matrix. Repeat the aforementioned procedures for the other jumps until the last damage state, i.e. failure state.



(a) Flow Chart



(b) Scheme of Randomly Sampling

Figure 5 Illustration of Fundamental Theory of Markov Chain Model

3. Case Study

3.1 Principles for Case Selection

In Section 2, the methodology used to assess/ evaluate the reliability of WT blades is presented, with the focus on Discrete Markov Chain Model. As a hybrid of the physics-based and the data-driven methods, Discrete Markov Chain Model does not require a closed-form equation characterizing the physical crack/defect propagation, which extends the application of Discrete Markov Chain Model. The essential input data is the prior information which stems from two resources, namely G2D database and fracture mechanics analysis/ the laboratory test results. G2D database is the focused data resource in the RATZ project, while the laboratory test results provide some supplementary information. In light of the complicated damage propagation paths, the application of the simplified crack propagation model is subjected to many limitations and can only provide a decision maker with quite general knowledge regarding the damage propagation rate. Discrete Markov Chain Model is thus chosen as a primary methodology for constructing the reliability model. Decision-making and cost estimation are based upon the stochastic damage propagation time series generated by Discrete Markov Chain Model, which will be detailed in another separate report (Cost modelling and decision-making ISSN 1901-726X DCE Technical Report No. 261). The case study is to mainly demonstrate how Discrete Markov Chain Model is used to simulate the stochastic damage propagation for reflect the primary concerns of 'Transverse cracks' and 'Root area& Transition zone cracks' in the RATZ project.

For 'Transverse cracks', there are two sources of information used to develop the reliability models. The G2D database provides the in-history failure records each of which includes the failure mode, the time to the observed damage (with respect to the start-up of operation), the damaged position (the distance with respect to the blade root), damage category, and the other information. The second data source refers to the laboratory tests which provide some basic information on the composite material's properties. For 'Root Area& Transition Zone cracks', a simplified reliability model is used. The failure scenario of 'Transverse cracks' is chosen as the major demonstration case, while the damages on 'Root area& Transition zone cracks' will be qualitatively investigated.

3.2 Reliability Model Specifications

The basic WT design data are referred to a reference project detailed in a NREL-issued technical report. The design specifications of these WTs are based upon the offshore WTs with the average size installed in the United States. The basic technical design parameters are summarized in Table 3. It should be noted that the in-history failure records in G2D database are used to calibrate the transition probabilities. It should be noted that one blade in a wind turbine from the wind farm mentioned in [22] is considered in this case study

Visual inspection is the focused non-destructive testing method in the RATZ project, because it is the most commonly used technique in the wind industry. As proposed in Table 1, discrete probabilities of detection for five damage categories are recommended by the experts, and summarized in Table 4. The environmental data, e.g. wind or wave time series, is referred to the FINO3 database, with the time series of wind and wave shown in Figure 6.

Table 3 Basic Technical Parameters of Hypothetical Off-shore Wind Turbines

Parameters	Unit	Value
Number of wind turbines	-	128
Rated power	MW	4.71
Water Depth	m	30/100
Design life	Year	20
Maximum Capacity Factor	-	0.47
Drivetrain design	-	Geared
Distance from Shore	km	30

VI is the focused NDT method in this case study, because it is the most commonly used technique in the wind industry. As proposed in Table 2, discrete probabilities of detection for five damage categories are recommended by the experts, and summarized in Table 4.

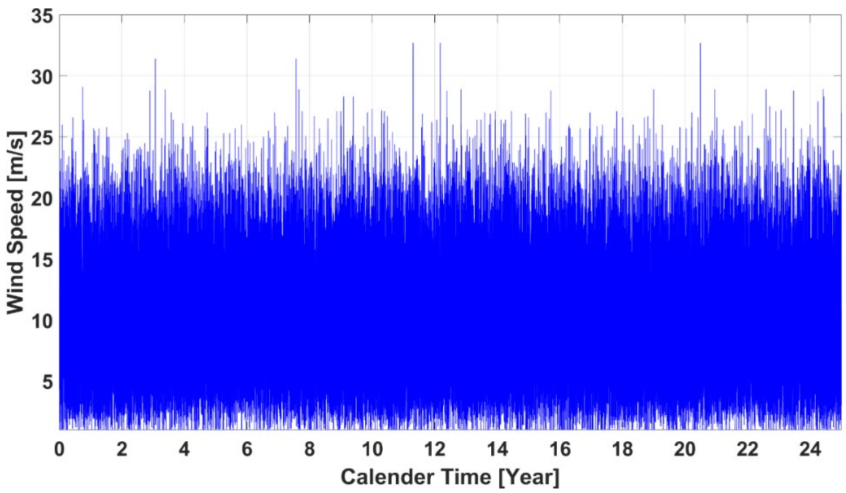
The maintenance actions are subject to the weather condition of the concerned wind farm. Normally, inspections and repairs are done in a benign weather condition. For onshore WTs, wind speed is the only dominating factor to be considered. For offshore WTs, wind speed and wave height should be considered to determine the appropriate time window. Generally, the following scenarios are encountered for offshore WTs:

- Scenario 1: There are a few discontinuous periods during which the weather limits for wind and wave are satisfied, but each of these periods does not last long enough for repair;
- Scenario 2: There is no period during which the weather limits for wind and wave are satisfied;
- Scenario 3: There is one or more periods during which the weather limits for wind and wave are satisfied. The periods are long enough to perform the maintenance.

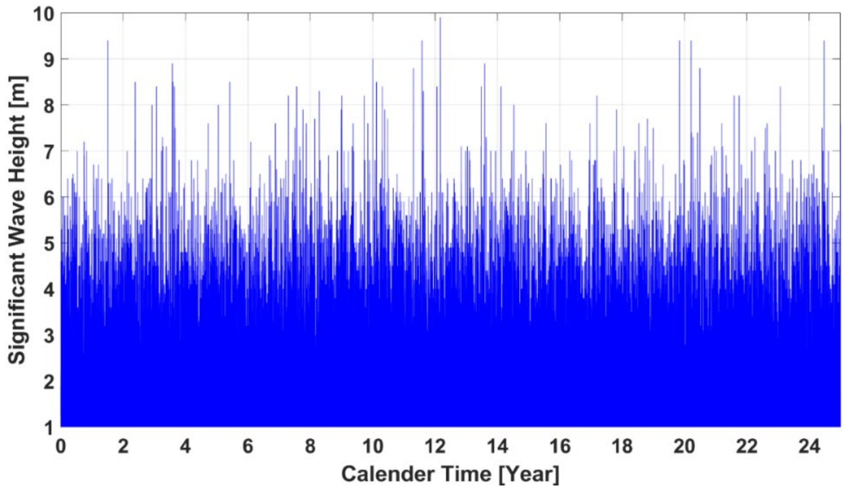
An appropriate time window is required to finish the inspection and/ or repair for a specific damage category. The waiting time for an appropriate time window should be taken into account in the decision-making process.

Table 4 Recommended Probabilities of Visual Inspection (assumed)

Damage Category	Probability Mass Function [%]	Probability of Detection [%]
D1	2	2
D2	5	7
D3	10	17
D4	20	37
D5	33	60
D6	40	100



(a) Wind Time Series



(b) Wave Time Series

Figure 6 Time Series of Wind and Wave Extracted from FINO3 Database

3.3 General Principles for Simulating Damage Propagations

The algorithm detailed in Section 2.4.3.2 is used to simulate the stochastic jump of damage states during the lifetime of WT blades. The whole lifetime is discretized to time slices, each of which denotes a basic time increment for calibrating the transition probabilities. A time increment could be any meaningful chronological time unit, but normally no larger than one month. The simulation starts with the intact condition, and follows all the basic assumptions in the Discrete Markov Chain Model, namely a jump is only achieved between two consecutive damage states. Due to the nature of random sampling, the simulated time series of damage propagation should be stochastic, which is typically reflected by:

- The stochastic sojourn time (also known as the stay duration) of each damage state;
- The stochastic number of reachable damage states, e.g. the stochastic jump stops and stays at a specific damage state for the rest of lifetime.

Due to the uncertainty associated with the random jumping, a large amount of simulations are required to characterize the expected (average) crack/defect propagation. Based upon these probabilistic damage propagation realizations, the mean maintenance cost, as well as the confidence interval, can be estimated to give the information on the maintenance cost uncertainty to a decision maker. Based upon the algorithm detailed in Section 2.4.3.2, *N* simulations are generated, which are exported as a data file for the subsequent decision-making analysis and cost estimation.

Besides the probabilistic damage propagation realizations, a decision maker should also need the pre-defined maintenance strategies to make decisions, when a specific damage is detected. A maintenance strategy is usually composed of three fundamental aspects, namely the inspection method, the inspection interval and some pre-defined decision alternatives (e.g. repairs) to be done after the inspections have been performed. These fundamental aspects, like some basic building blocks used to construct a system, constitutes the main framework of a maintenance strategy. There are some possible options of each of these fundamental aspects for a decision maker to choose from. Possible options for each fundamental aspect can be freely combined with the options of the other two fundamental aspects. For example, one of possible inspection methods is combined with one of inspection intervals and one decision alternative, as illustrated in Figure 7.

- Decision Alternative 1
  - Action 1 – If a damage of damage category 1 is detected, no action will be taken;
  - Action 2 – If a damage of damage category 2 is detected, minor repair will be done;
  - Action 3 – If a damage of damage category 3 is detected, moderate repair will be done;
  - Action 4 – If a damage of damage category 4 is detected, moderate repair will be done;

  - Action 5 – If a damage of damage category 5 is detected, major repair will be done.
- Decision Alternative 2
  - Action 1 – If a damage of damage category 1 is detected, no action will be taken;
  - Action 2 – If a damage of damage category 2 is detected, no action will be taken;
  - Action 3 – If a damage of damage category 3 is detected, moderate repair will be done;
  - Action 4 – If a damage of damage category 4 is detected, moderate repair will be done;
  - Action 5 – If a damage of damage category 5 is detected, major repair will be done.
- Decision Alternative 3
  - Action 1 – If a damage of damage category 1 is detected, no action will be taken;
  - Action 2 – If a damage of damage category 2 is detected, no action will be taken;
  - Action 3 – If a damage of damage category 3 is detected, no action will be taken;
  - Action 4 – If a damage of damage category 4 is detected, moderate repair will be done;
  - Action 5 – If a damage of damage category 5 is detected, major repair will be done.
- Decision Alternative 4
  - Action 1 – If a damage of damage category 1 is detected, no action will be taken;
  - Action 2 – If a damage of damage category 2 is detected, no action will be taken;
  - Action 3 – If a damage of damage category 3 is detected, no action will be taken;
  - Action 4 – If a damage of damage category 4 is detected, no action will be taken;
  - Action 5 – If a damage of damage category 5 is detected, major repair will be done.
- Decision Alternative 5 (similar to corrective maintenance)
  - Action 1 – If a damage of damage category 1 is detected, no action will be taken;
  - Action 2 – If a damage of damage category 2 is detected, no action will be taken;
  - Action 3 – If a damage of damage category 3 is detected, no action will be taken;
  - Action 4 – If a damage of damage category 4 is detected, no action will be taken;
  - Action 5 – If a damage of damage category 5 is detected, no action will be taken.

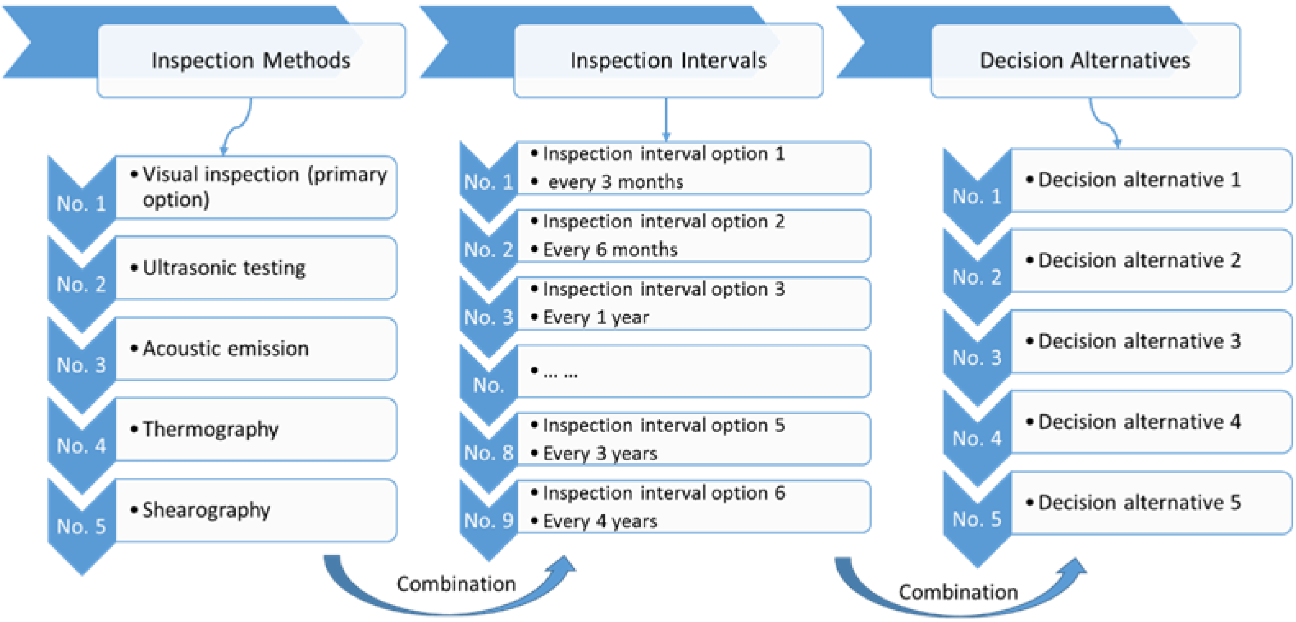


Figure 7 Illustration of Combinations of Maintenance Strategies and Inspection Intervals

The methodology regarding decision-making is mainly based upon Bayesian pre-posterior inference and is detailed in another separate report (Cost modelling and decision-making ISSN 1901-726X DCE Technical Report No. 261). The major steps of decision-making is briefly described in this report, as summarized below:

- Step-1: Choose the inspection method(s) and the possible inspection intervals;
- Step-2: Define decision alternatives/ rules;
- Step-3: Generate stochastic damage propagation process based upon Discrete Markov Chain Model;
  A Discrete Markov Chain Model is used to generate *N* lifetime realizations of the propagation of the damage. For each of the *N* realizations, the maintenance costs, including wait time, inspection, technician, repair, vessel, downtime, replacement (if a total collapse occurs), are calculated, and the expected value of the total costs are estimated as the mean of the *N* realizations.
- Step-4: Combine different options of inspection intervals and decision rules;
  Inspection method, inspection intervals and decision alternatives can be freely combined, as illustrated in Figure 2.
- Step-5: Choose the cost-optimal maintenance strategy, by comparing the expected costs corresponding to all the possible decision combinations.
  The maintenance strategy with the minimum cost is chosen as the cost-optimal maintenance strategy. This recommends the first optimal inspection time and the maintenance actions.

The procedure is repeated to choose the second optimal inspection time and the maintenance actions, and so on for the whole lifetime.

3.4 Demonstration Case – Transverse Cracks

3.4.1 Observations of Transverse Cracks and Calibrated Transition Probabilities

As mentioned in Section 2.4.3.2, there are a total of seven states in the Discrete Markov Chain Model. The number of collapsed blades is assumed based upon an empirical failure rate which is determined by engineering experience (0.0037 per year) or the recommended rate(s) in well-recognized international codes (e.g. 0.0005 per year in IEC 61400 Rev.4 [21]). These observations, as summarized in Table 5, provide the prior information used for calibrating the transition probabilities. With the almost same input numbers, the calibrated transition probabilities are almost the same as summarized in Table 6.

Table 5 Summary of Damage Observations of Different Categories — Transverse cracks

Damage Category	0	1	2	3	4	5	6
No. of Observations	103	187	572	419	64	13	7

Table 6 Summary of Transition Probabilities— Transverse cracks

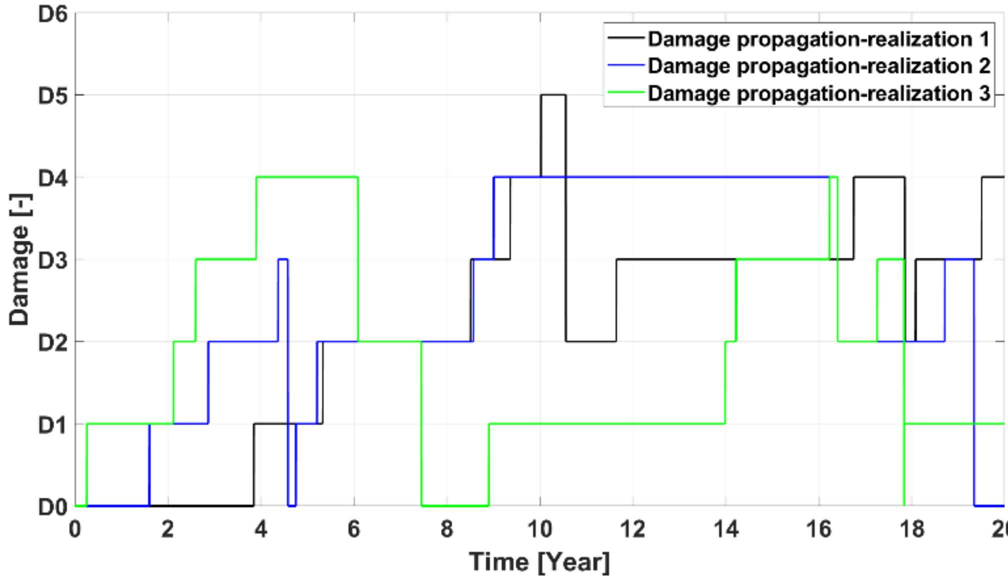
Transition Probability	$P_{0\|1}$	$P_{1\|2}$	$P_{2\|3}$	$P_{3\|4}$	$P_{4\|5}$	$P_{5\|6}$
	0.0018	0.0023	0.0009	0.0003	0.0004	0.0046

3.4.2 Demonstration of Damage Propagation Realizations

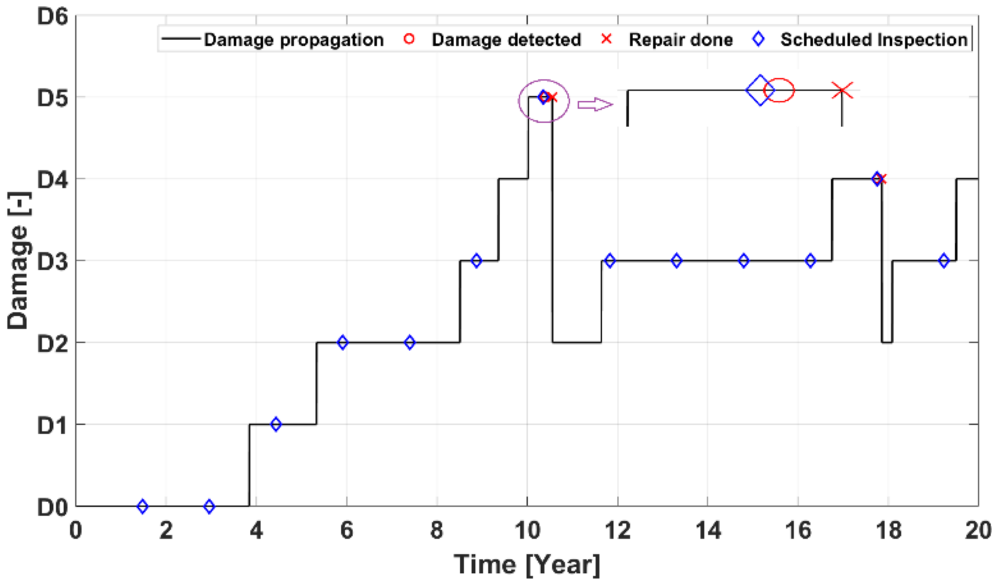
Based upon the description in another separate report (Cost modelling and decision-making ISSN 1901-726X DCE Technical Report No. 261), there are 45 combinations, namely visual inspection, 9 inspection intervals and 5 decision alternatives are combined. For each of 45 combinations, *N* simulations (*N*=10000) are done. The cost-optimal maintenance strategy as detailed in another separate report (Cost modelling and decision-making ISSN 1901-726X DCE Technical Report No. 261) is that an inspection interval of 1.5 years and decision alternative 2. Therefore, the stochastic damage propagation corresponding to this maintenance strategy will be demonstrated in this section. Three realizations of the stochastic damage propagation for the cost-optimal maintenance strategy are shown all together in Figure 8 (a), while Figure 8 (b)~(d) separately show either of the three realizations.

The stochastic property of the Discrete Markov Chain Model is reflected from two perspectives as summarized below:

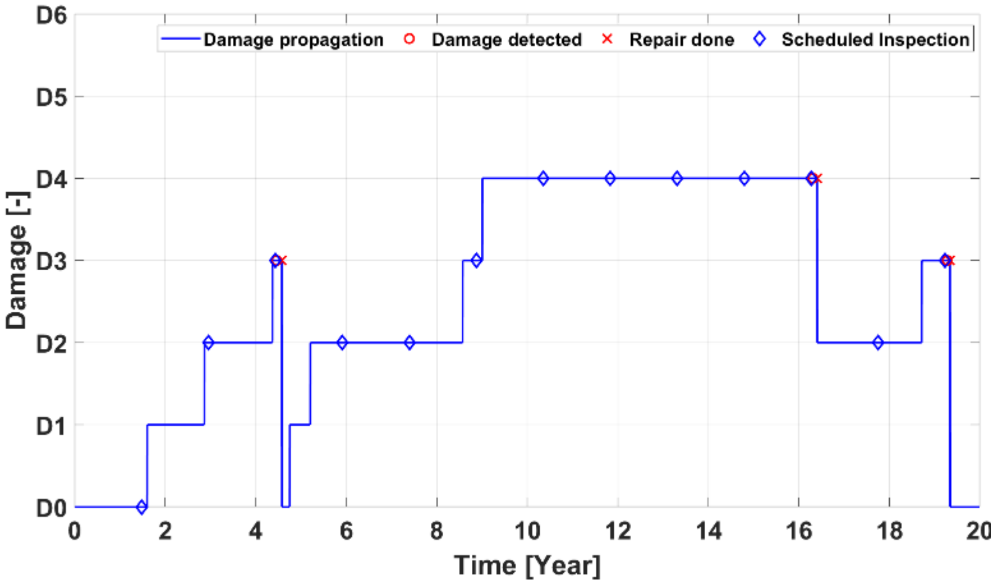
- The sojourn time (stay duration) of each damage state (either of D1~D5) is stochastic as clearly shown in Figure 4;
- The degradation rate (namely how fast a damage propagates from one damage state to the next more severe damage state) is different in each simulation or how fast a blade proceeds to a total collapse (namely to the damage category D6).



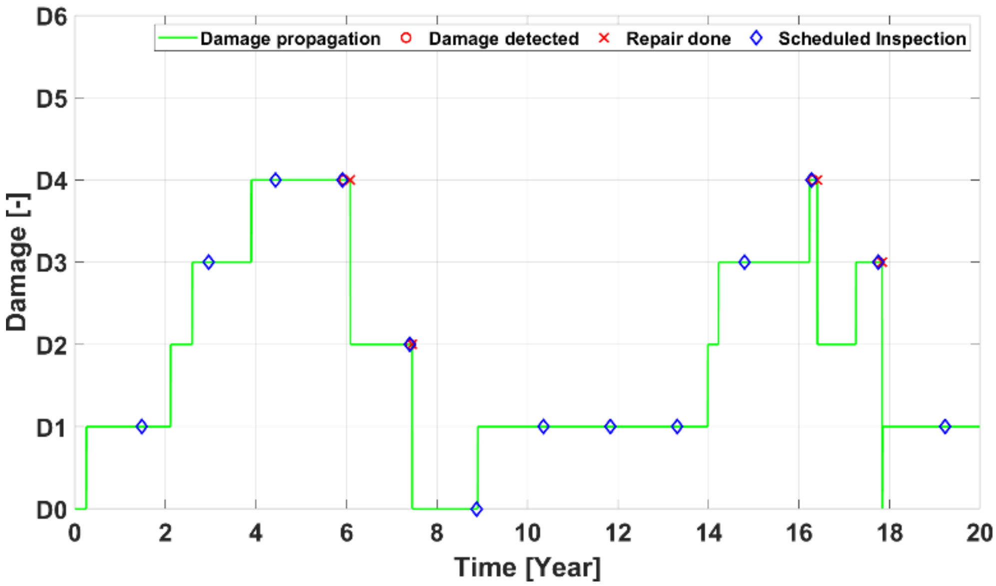
(a)



(b) Damage Propagation – Realization 1



(c) Damage Propagation – Realization 2



(d) Damage Propagation – Realization 3

Figure 8: Realizations of the Stochastic Damage Propagation

In Figure 8, each blue diamond represents the scheduled inspection time. Each red circle represents that an inspection is done and a damage is detected using the assumed PoDs for visual inspection as summarized in Table 4. The fact that a blue diamond and a red circle coincides indicates that visual inspection detects the damage at the scheduled inspection time. Otherwise, there is only one blue diamond at each scheduled inspection time. Each red cross represents that the detected damage is repaired, based upon a pre-defined decision alternative. There is a time lag between a diamond, a red circle and a red cross, which represents the repair time and also the wait time for an appropriate time window. The markers are overlapped in Figure 4, which is difficult to identify. An enlarged view is thus plotted for one inspection time in Figure 8(b), where the time lag between the blue diamond and the red circle denotes the wait time for an appropriate time window and the time lag between the red circle and the red cross denotes the repair time and/ or the wait time for an appropriate time window (because the repair works may be interrupted by a harsh weather condition).

After the repair is done, each line drops down to the pre-defined post-repair condition based upon the assumptions as summarized below.

- For Damage Category 2& 3, the damaged portion of a blade recovers to the intact condition after repair;
- For Damage Category 4& 5, the damaged portion of a blade recovers to Damage Category 2 after repair;

As summarized in Table 1, a decision alternative indicates a critical damage. No repair is done for the detected damage that is less severe than this critical damage. For instance, it can be seen from Figure 8 (b)~(d) that at some inspections no damage is detected (no red circle) and at others a damage is detected and a repair is done. Based upon the assumptions regarding the post-damage condition as summarized in Table 1, the damage level drops to D0, if the damage is at D3; or it drops to D2, if the damage is at D4 or D5. Figure 8 (b)~(d) also show that for most scheduled inspection times visual inspection cannot detect the damage, which indicates that the probability of detection for smaller damage sizes is relatively low.

3.5 Demonstration Case – Root Area& Transition Zone Cracks

3.5.1 Assumptions for Transition Probabilities

The simulation-based methodology can be applied to 'Root Area& Transition Zone Cracks'. However, due to the concerns mentioned in Section 2.1, the transition probabilities cannot be directly calibrated against the observations. Alternatively, the transition probabilities can be taken as dummy example values based upon the knowledge of the typical crack/defect propagation of composites. By doing this, these assumed probabilities can approximately reflect how fast a damage propagates. The knowledge could be obtained through the engineering experience and the theoretical models established in the other industries (e.g. oil& gas), which are based to qualitatively answer the following two questions:

- What is the collapse rate (the frequency of occurrence of D6)?
- How fast a damage propagates from D1 to D6?

Basically, the answers to the above two questions can characterize the crack/defect propagation route/path of composites. The crack/defect propagation route/path is closely associated with the design specification. The material properties and the geometry of the blades are two dominating factors to be considered in the design specification. The loads exerted upon the blade profile are closely associated with the blade geometry, especially the length. These dominating factors should be considered, when the assumptions are made for the transition probabilities.

Without any prior information on the damage propagation at the root area& transition zone, a crack/defect is assumed to propagate in the following two manners:

- The damage propagates approximately linearly ;
- The damage propagates nonlinearly (approximately exponential/ polynomial);

These two types of damage propagation can answer the second aforementioned question. The transition probabilities is assumed to be modelled in such a way that the blade collapses once or twice in average during the lifetime, and using the decision alternative 5 (corrective maintenance) and a 2-year inspection interval (a common inspection interval for WT blades). The assumed transition probabilities are summarized in Table 7 and Table 8. It should be noted that these assumed transition probabilities are based upon a rough estimation.

Table 7 Summary of Transition Probabilities ('Root Area & Transition Zone Cracks') – Approximately Linear Propagation

Transition Probability	$P_{0\|1}$	$P_{1\|2}$	$P_{2\|3}$	$P_{3\|4}$	$P_{4\|5}$	$P_{5\|6}$
	0.0007	0.0009	0.0004	0.0004	0.008	0.0009

Table 8 Summary of Transition Probabilities ('Root Area & Transition Zone Cracks') – Nonlinear Propagation (approximately exponential/polynomial propagation)

Transition Probability	$P_{0\|1}$	$P_{1\|2}$	$P_{2\|3}$	$P_{3\|4}$	$P_{4\|5}$	$P_{5\|6}$
	0.0005	0.0007	0.02	0.3	0.5	0.8

3.5.2 Demonstration of Damage Propagation Realizations

The decision alternative 5 combined with a 2-year inspection interval is focused in this demonstration case. With the assumed transition probabilities, *N* simulations (*N*=10000) are done for the two manners of the damage propagation as mentioned in Section 3.5.1. The expected (average) stochastic crack/defect propagation, together with 3 of all realizations, is plotted in Figure 9 (for the case where a crack/defect propagates approximately linearly) and Figure 11 (for the case where a crack/defect propagates nonlinearly). The red curve represents the expected crack/defect propagation, and gives a decision maker a clear picture of how fast a crack/defect propagates. Figure 10 shows one realization of all *N* simulations for the case where a crack/defect propagates approximately linearly. Figure 12 shows one realization of all *N* simulations for the case where a crack/defect propagates nonlinearly. The meanings of the markers in Figure 10 and Figure 12can be referred to Section 3.4.2.

It can be seen from Figure 9 that the expected crack/defect propagates almost linearly, and it takes a longer time for a crack/defect jumps to the collapse state which is due to the relatively low transition probabilities. In Figure 11, the nonlinear propagation is observed and a crack/defect jumps to the collapse state very quickly, which is due to the relatively higher transition probabilities (to achieve the target of a blade collapsing once or twice during the design life). For the case where a crack/defect propagates approximately linearly, the sojourn time (stay duration) of each damage state is relatively long, which can be explained in such a way that the low transition probabilities indicate a less likelihood of jumping from a damage state to the next more severe state as illustrated in Figure 9. Accordingly, the time for 1st passage of D6 is relatively later than the case of nonlinear crack/ defect propagation. On the contrary, for the case where a crack/defect propagates nonlinearly, the transition probabilities are much greater for the case of linear crack/ defect propagation, which results in much shorter the sojourn time (stay duration) of each damage state, especially D3, D4, and D5 as illustrated in Figure 11. Accordingly, the time for 1st passage of D6 is relatively earlier than the case of linear crack/ defect propagation, and the blade collapses one more time.

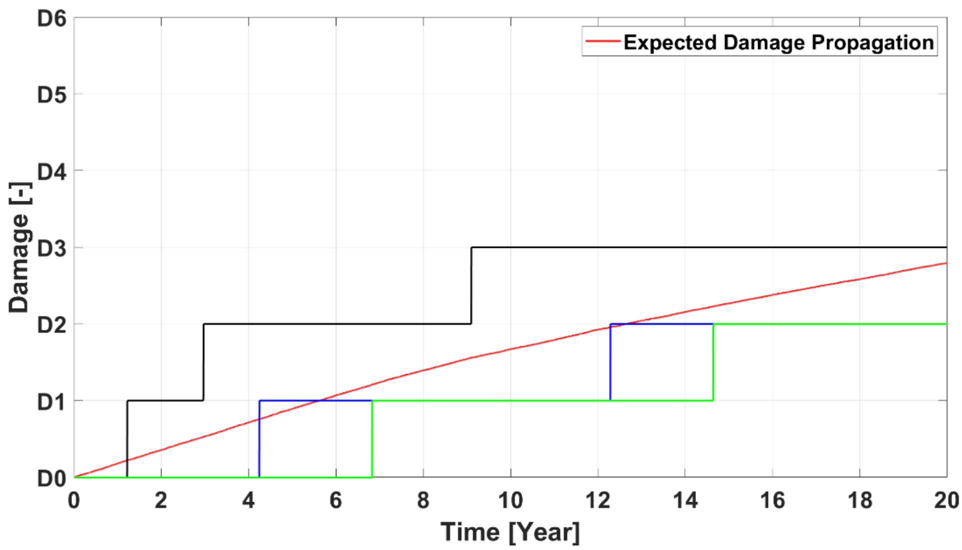


Figure 9: Illustration of Expected Damage Propagation – Approximately linear damage propagation

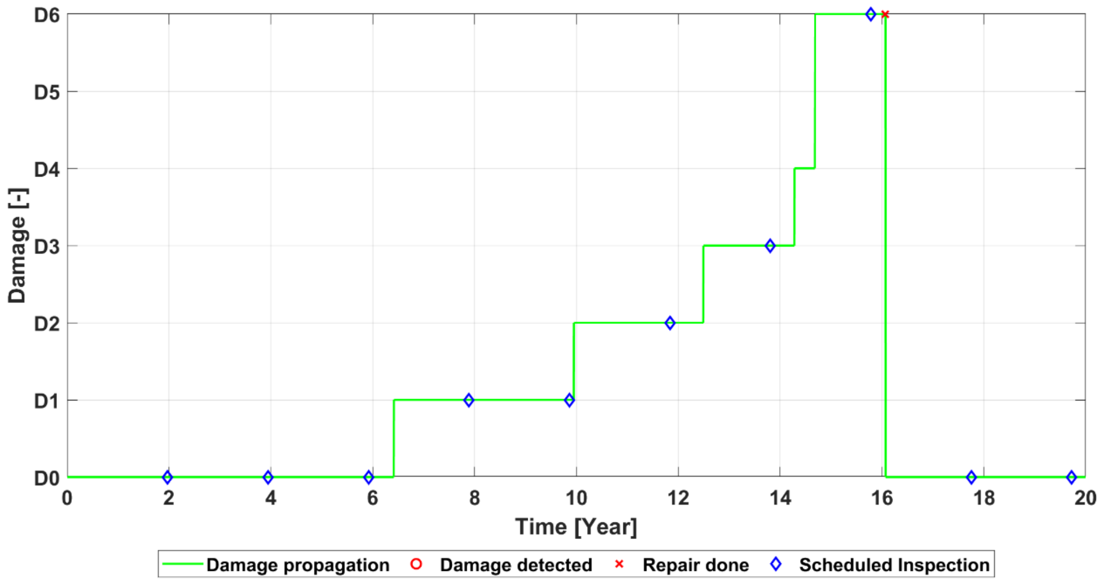


Figure 10: A Realization of the Stochastic Damage Propagation – Approximately linear damage propagation

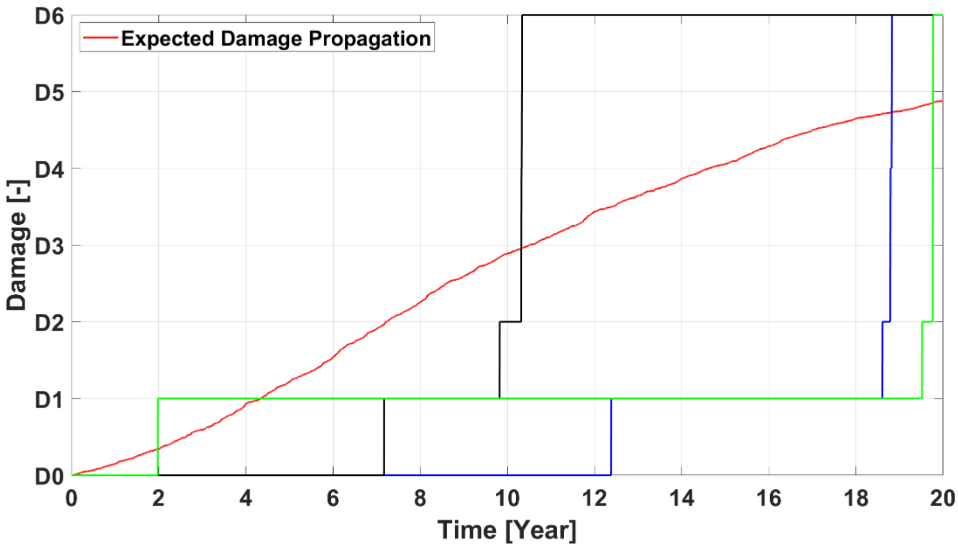


Figure 11: Illustration of Expected Damage Propagation – Nonlinear (approximately exponential/ polynomial) damage propagation

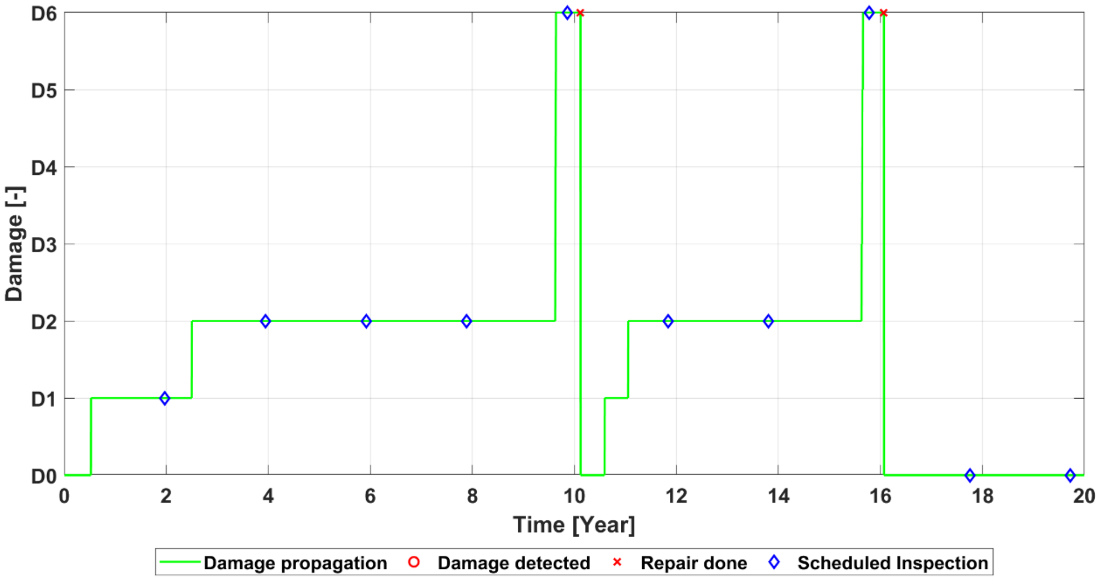


Figure 12: A Realization of the Stochastic Damage Propagation – Nonlinear (approximately exponential/ polynomial) damage propagation

4. Conclusions and Recommendations

A simulation-based method, namely combining a Discrete Markov Chain model with Bayesian decision tree theory, is primarily investigated in this WP in order to identify cost-optimal condition-based maintenance strategies where the cost-optimal inspection method and interval, and the corresponding decision alternative are identified. The methodology for simulating the probabilistic crack/defect propagation based upon the Discrete Markov Chain model is implemented and illustrated in a case study of this report.

The accuracy of the Discrete Markov Chain model depends upon the in-history failure records categorized based upon the five-level damage categorization scheme as illustrated in Figure 1. In this sense, the information on the failure records extracted from the database is used to estimate the prior transition probabilities used for the first demonstration case ('Transverse Cracks'). For the second demonstration case ('Root Area & Transition Zone Cracks'), the transition probabilities can only be estimated based upon the engineering experience instead of being calibrated against observations. This approximate treatment for the second demonstration case can only be used as a rough estimation.

Generally speaking, the Discrete Markov Chain model can be applied to the failure modes mentioned in the demonstration cases. It can be concluded from the case study that:

- The crack/ defect propagation rate is highly related to the transition probabilities. The crack/defect propagation route/path (either almost linear or nonlinear propagation) can be qualitatively estimated, namely whether it propagates linearly or nonlinearly, based upon the calibrated transition probabilities;
- The greater transition probabilities indicate that a crack/ defect propagates and reaches to the collapse state much faster than the lower transition probabilities; in addition, the number of the blade collapse for the case where a crack/ defect propagates nonlinearly (corresponding to higher transition probabilities) is higher than that for the case where a crack/ defect propagates almost linearly (corresponding to lower transition probabilities)

The Discrete Markov Chain Model developed for the RATZ project is a simplified methodology that characterizes the crack/ defect propagation from the probabilistic point of view. This model can be easily implemented in a computer code, however, it is unable to interpret the failure mechanisms for 'Transverse Cracks' and 'Root Area & Transition Zone Cracks'. Therefore, it is recommended that a quantitative fracture mechanics model be developed from the perspective of failure mechanism, and be used together with the Bayesian decision tree to do cost-optimal inspection planning.

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